Bonneville Power Administration

Heat Pump Water Heater Laboratory Testing Results

PRESENTED TO THE HPWH ADVISORY COMMITTEE ON:

July 14, 2011

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Agenda

- Lab Findings
  - EF and 1st hr Rating
  - Performance Mapping & Operating Range
  - Draw Patterns
- Space Heating/Cooling Interaction & Energy Use Estimates
  - Baseline Inputs
  - Field Data
  - Annual Temperature Profiles
  - COP Mapping
  - Garage, Basement and Interior Energy Use
  - Heating/Cooling System Interactions
  - Energy Savings Estimates

Project Goals

- Using a controlled laboratory environment, evaluate the performance of HPWHs in Pacific NW conditions.
- Determine impacts of the HPWHs on the spaces where they are installed
- Estimate energy savings of the equipment

Equipment Examined

GE
50-gallon

AO Smith
80-gallon

Rheem
50-gallon

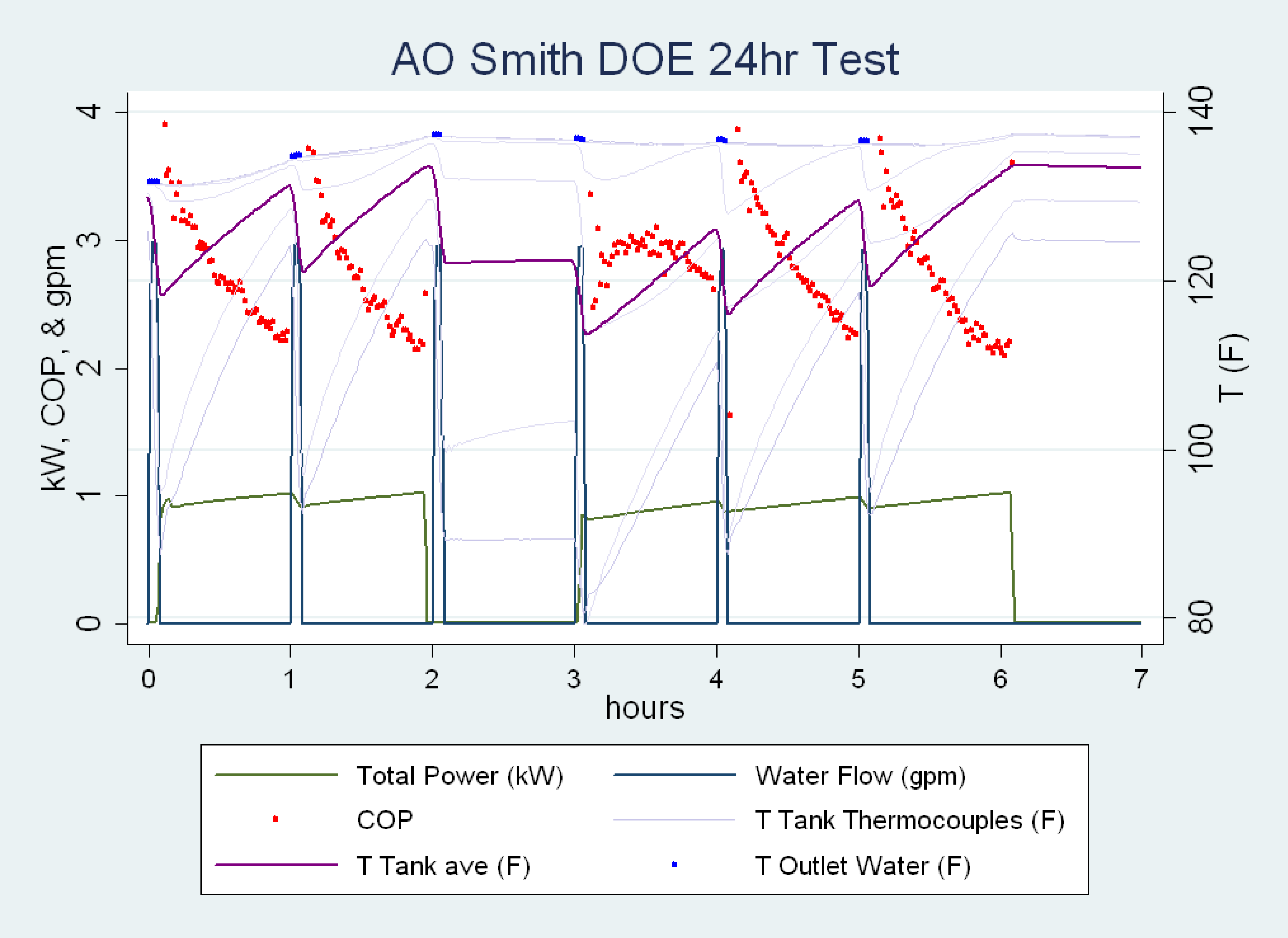
Measurement & Verification Plan

- Developed 1.5 yrs ago with help of advisory committee:
  - http://www.bpa.gov/energy/n/emerging_technology/pdf/HPWH_MV_Plan_Final_012610.pdf
- Conducted national lab search and selected the National Renewable Energy Lab (NREL) to perform the tests.

M&V Plan Overview

- M&V Plan consists of multiple test types:
  - COP Mapping
    - as a function of both ambient air conditions and water temperatures
    - also includes restricted airflow testing
  - DOE Standard Rating Points
    - 24 hr Energy Factor (EF) and 1st hr Rating
  - Operating Mode Explorations
    - determine under what conditions equipment switches from heat pump to resistance element use
  - Draw Profiles
    - simulated use tests

24 hr EF Test Example



First 7 hrs.

6 draws of 10.7 gal.

Only compressor used to heat tank.

Tank in standby mode for remaining 17 hrs. Ave tank T drops as expected within T-stat dead-band.

24hr, 1hr Results & Spec. Comparison

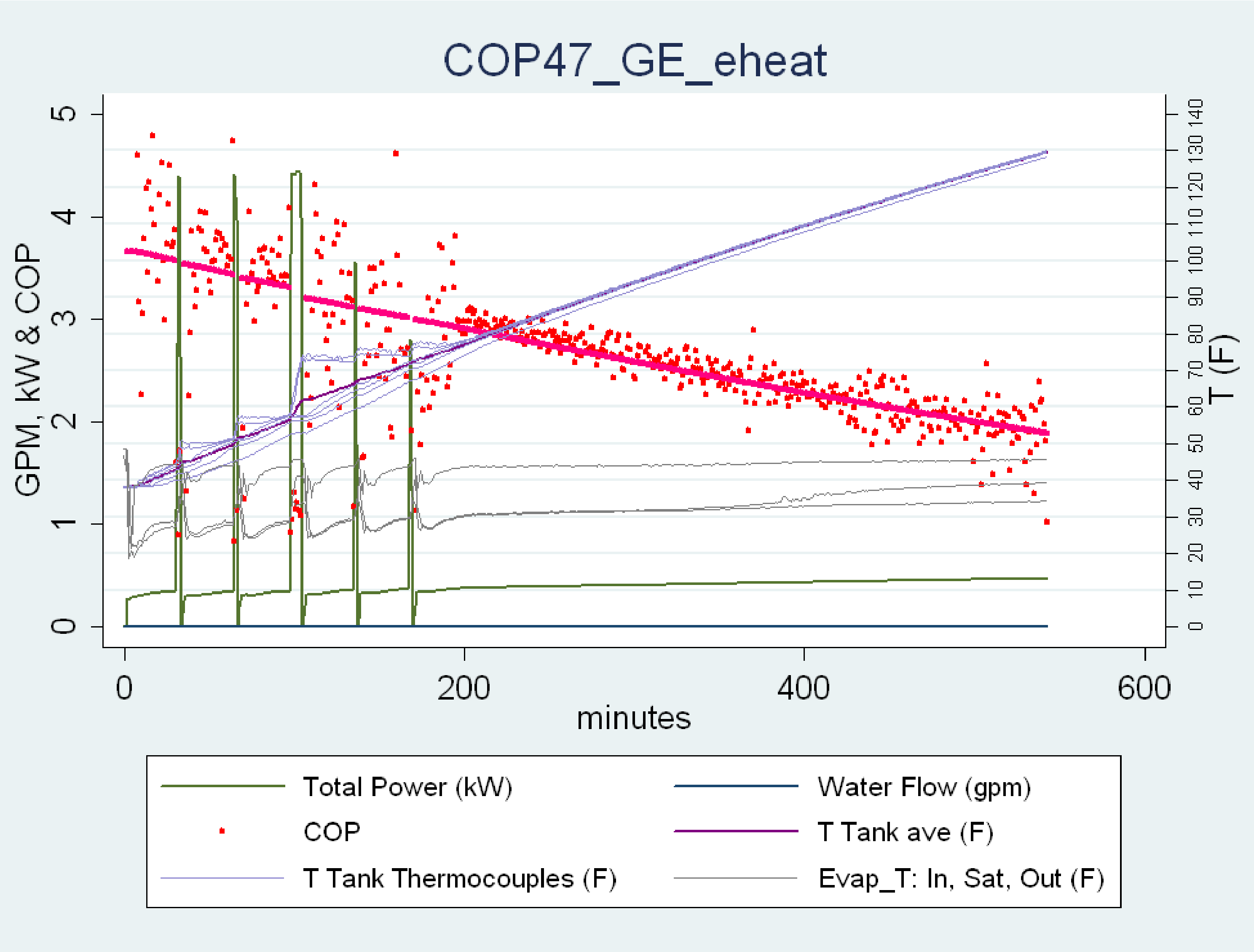
		GE GeoSpring		Rheem HP50		AO Smith Voltex PHPT-80	
	Units	**Lab Meas.**	**Spec. Sheet**	**Lab Meas.**	**Spec. Sheet**	**Lab Meas.**	**Spec. Sheet**
Upper* Element	kW	4.5		2.5	2.5	4.5	
Lower* Element	kW	4.5		2.5	2.5	2	
Compressor Power**	W	300-700	700	450-1100	--	550-1100	700
Standby Power	W	3	2	8	--	8	--
Fan* Power**	W	5-10	--	11	--	85	--
Pump Power	W	na	na	73	--	na	na
Airflow Path:		Inlet on sides. Exhaust to back.		Inlet on top. Exhaust to sides.		Inlet on left side. Exhaust to right side.	
Airflow	cfm	100-175	--	100	--	475	--
Refrigerant		R-134a		R-410a		R-134a	
Performance Characteristics Test Mode:		Hybrid		Energy Saver		Hybrid	
Tank Volume	gal	45.5	50	45.3	50	75	80
First Hr Rating	gal	61.7	63	70.5	67	87	84
Energy Factor	EF	2.41	2.35	1.69	2	2.29	2.33
Tank Heat Loss Rate	Btu/hr-F	3.8	--	5.1	--	3.9	--

*240V supply. Elements interlocked for GE and AO Smith, may operate in tandem for Rheem.

**range depends on water T and ambient T. Power increases with both.

***variable speed depends on conditions

COP Test Example



GE COP test at 47F ambient.

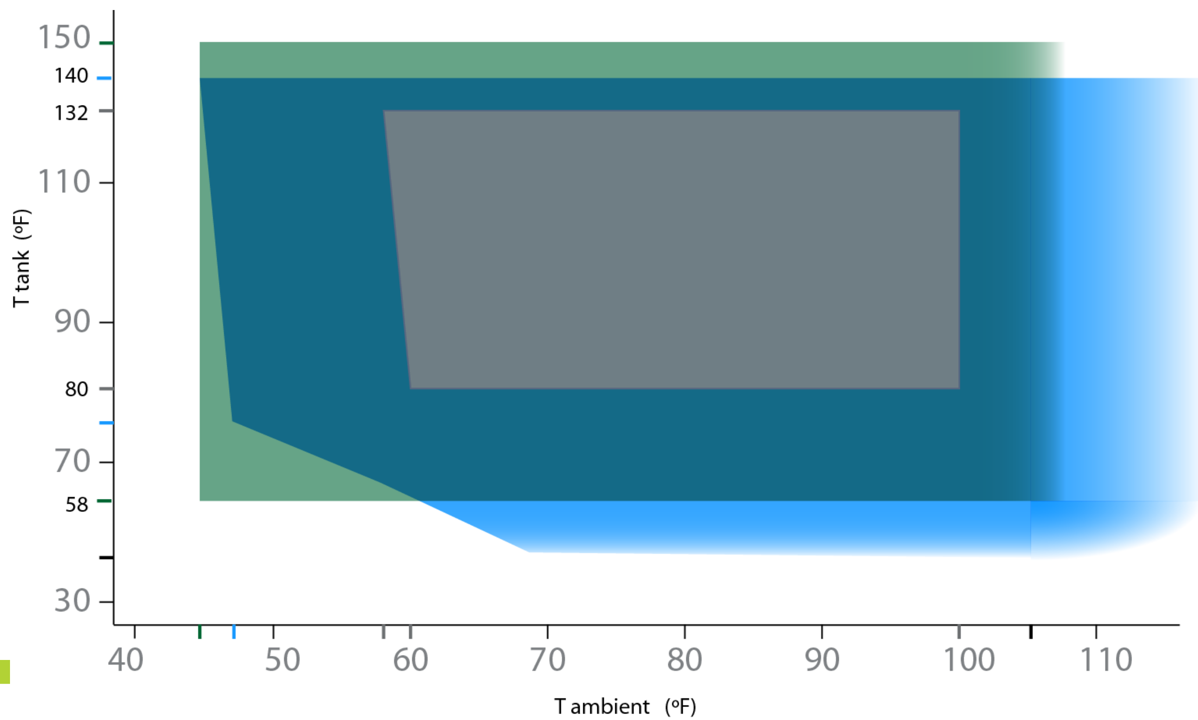
Pink line is fit to COP data.

At low water T, <80F, element cycles on/off with compressor due to coil frosting conditions.

Total of 11 COP-type tests conducted for each unit.

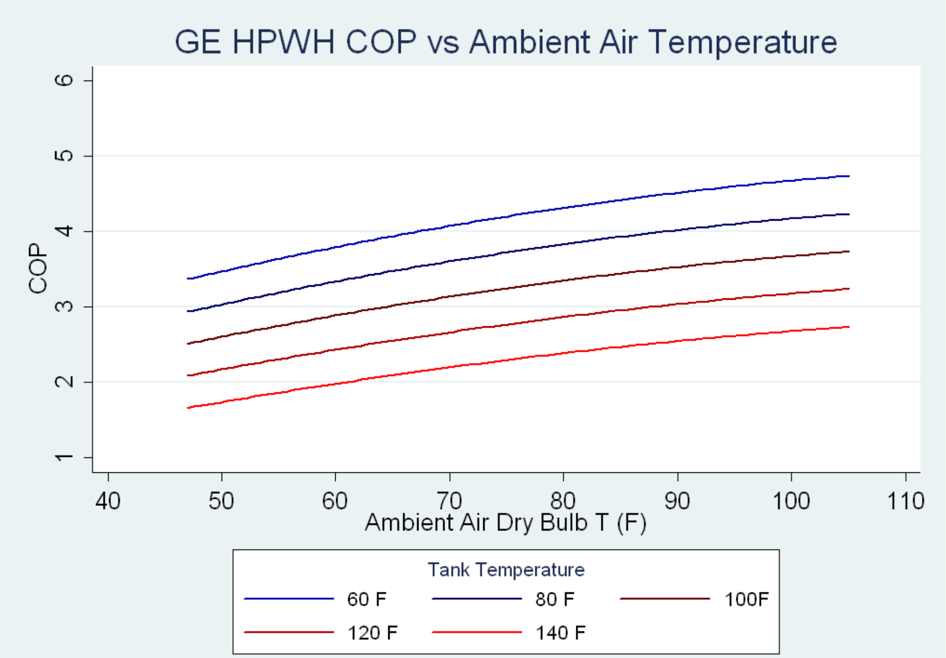
Compressor Operating Ranges

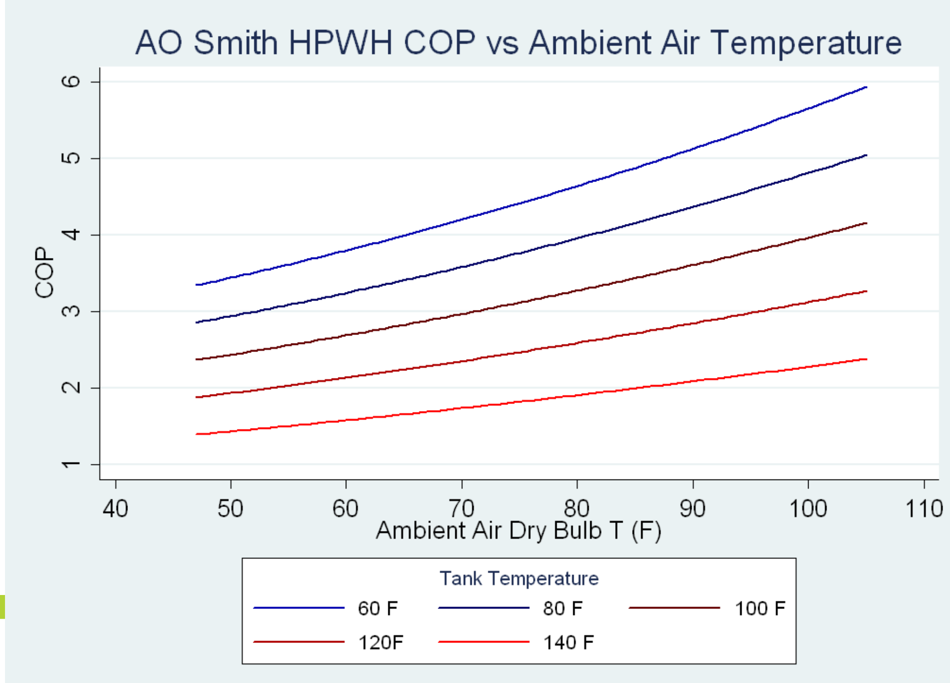
- Colored areas show ambient air T and ave tank T in which the compressor operates. Compressor cycles off at low T_{amb} & T_{Tank}
  - T_{amb} operation verified up to 105F – spec sheets indicate higher values (shown by fade).
  - Likewise, T_{Tank} verified up to 140F – spec sheet data indicates higher operation for some models.
- Green – AO Smith, Blue – GE, Gray -Rheem

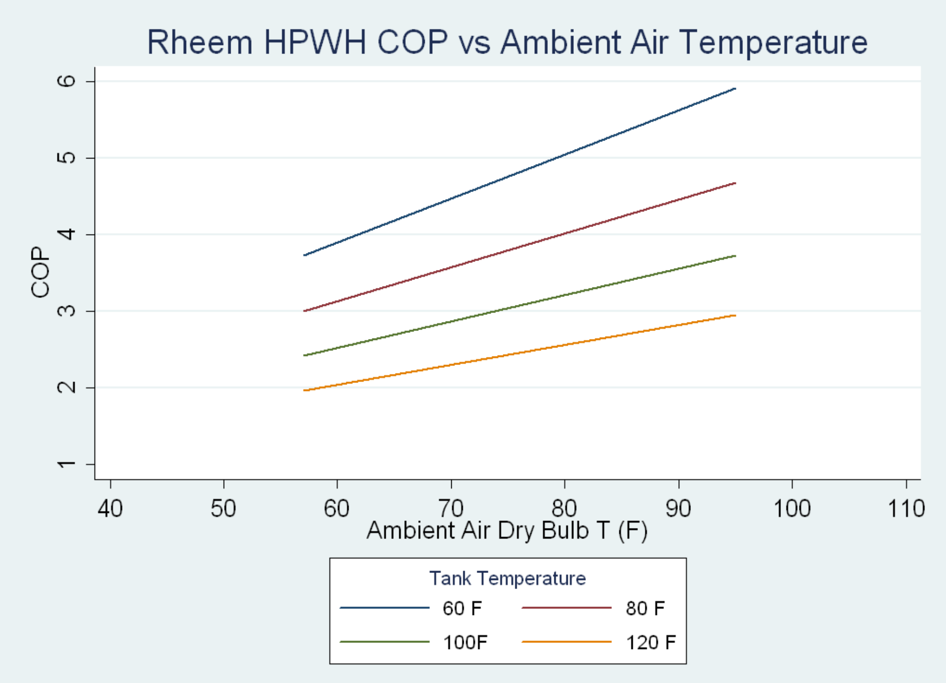


COP Mapping Results

- Compressor curves for 3 units.
  - COP depends strongly on T_{db} & T_{Tank} and less so on T_{wb}
- Empirical fits to measured data – not a unified model across units. Leads to different shaped curves which reflects different physical configurations.







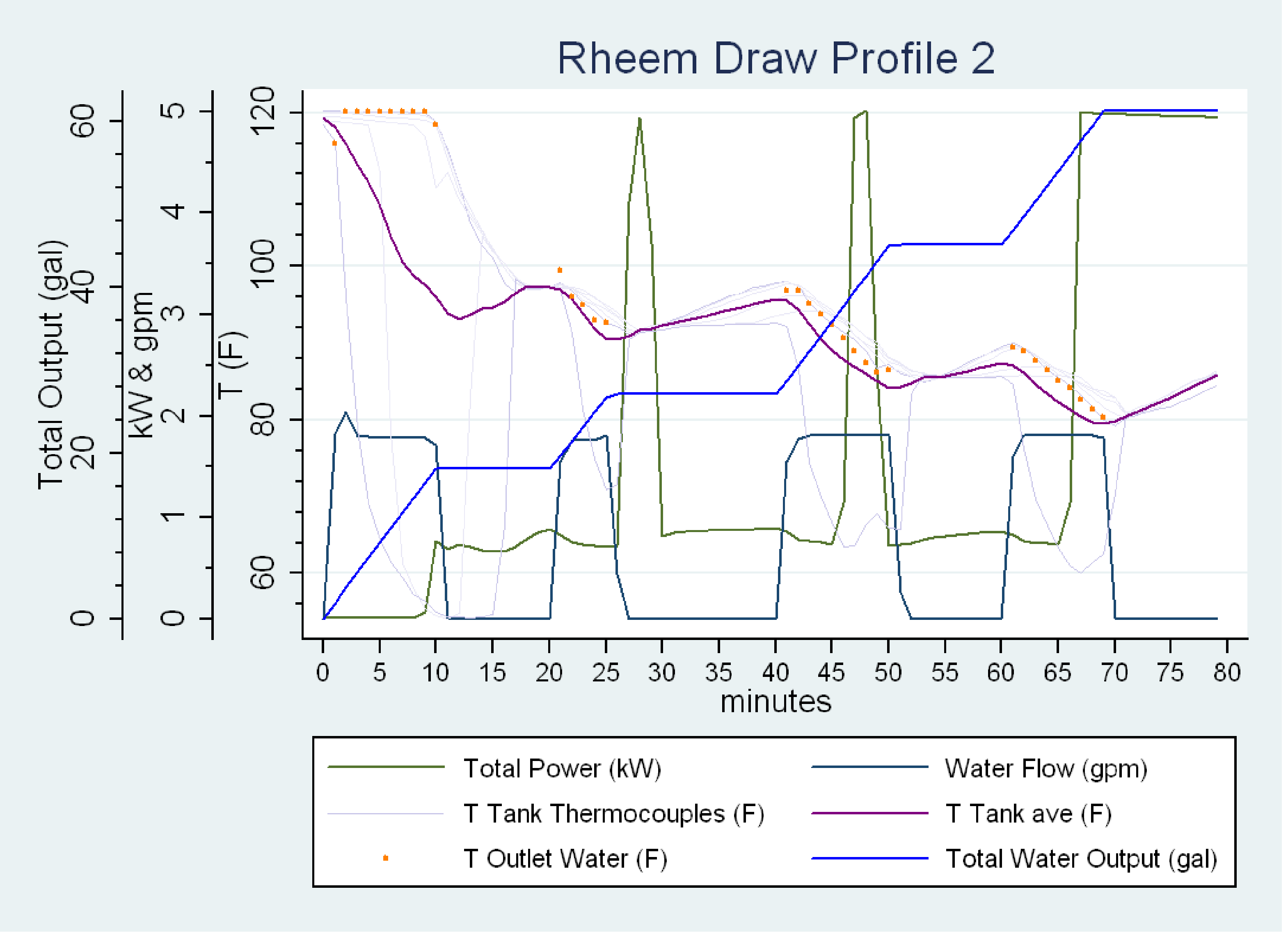
Compressor COP Map Results

- COP mapping created a full performance characterization of the equipment under any environmental condition
  - Empirical data used to create functional fits
- Measured the operational boundaries of the compressor

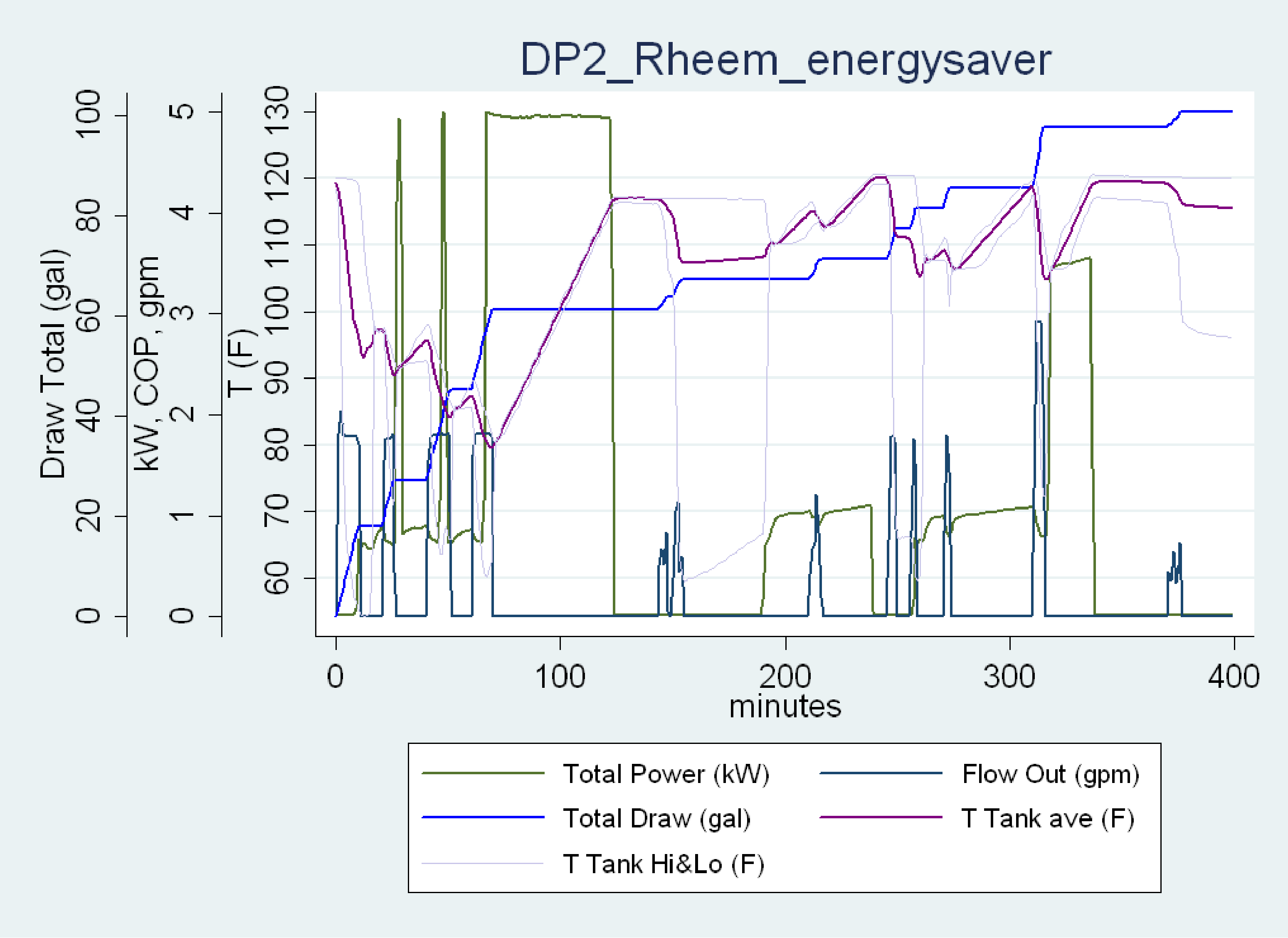
Draw Profile Findings

- Draw profile, DP-2:
  - 120F set point
  - 45F inlet water (winter season)
  - Two draw segments:
    - 1st is 4 showers in 1.5 hrs totaling 68 gallons
    - 2nd totals 40 gallons over 4 hours
- DP-2 shows interplay of tank capacity, compressor heating capacity, and resistance element use.

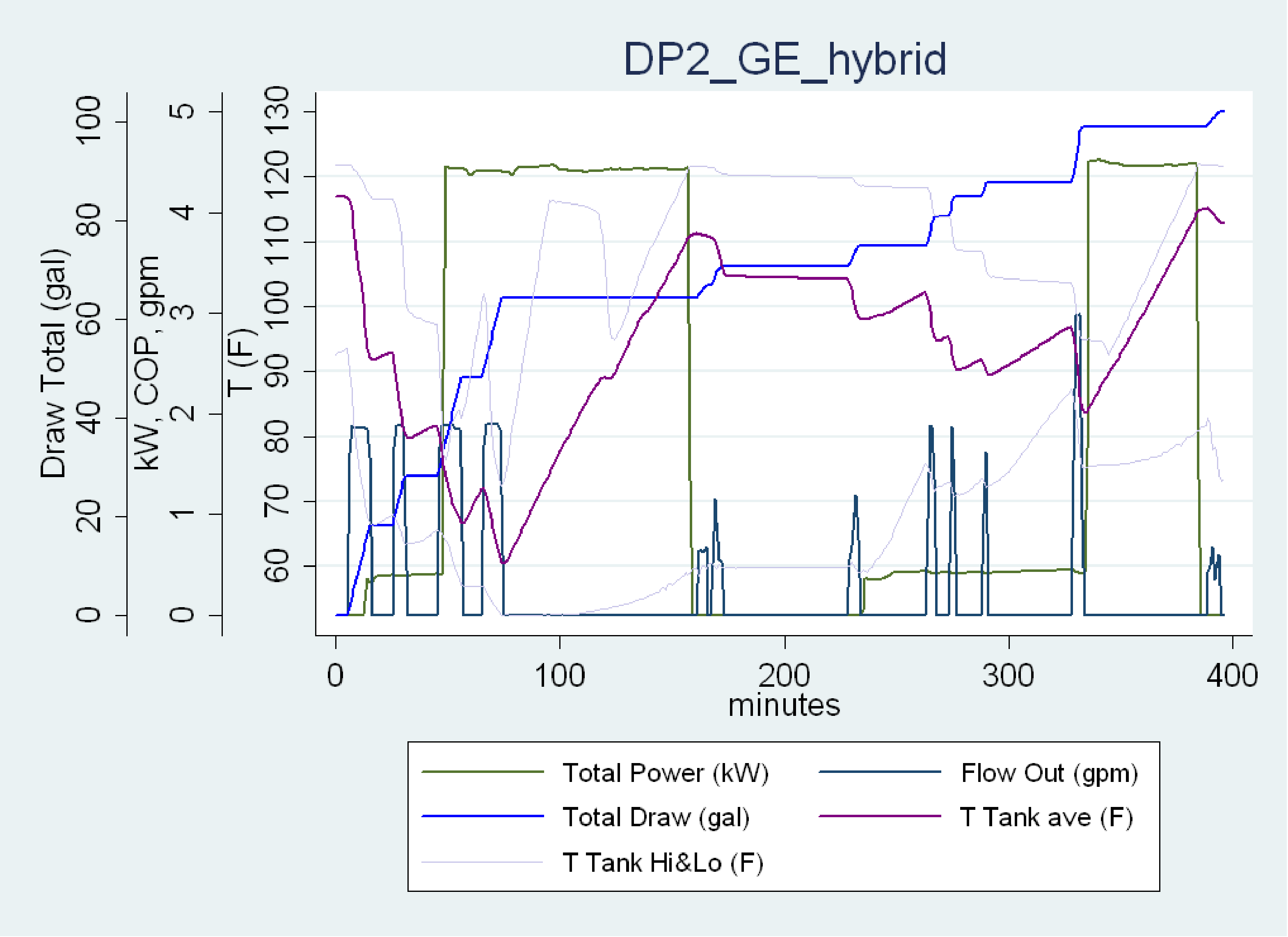
DP-2, First 80 minutes



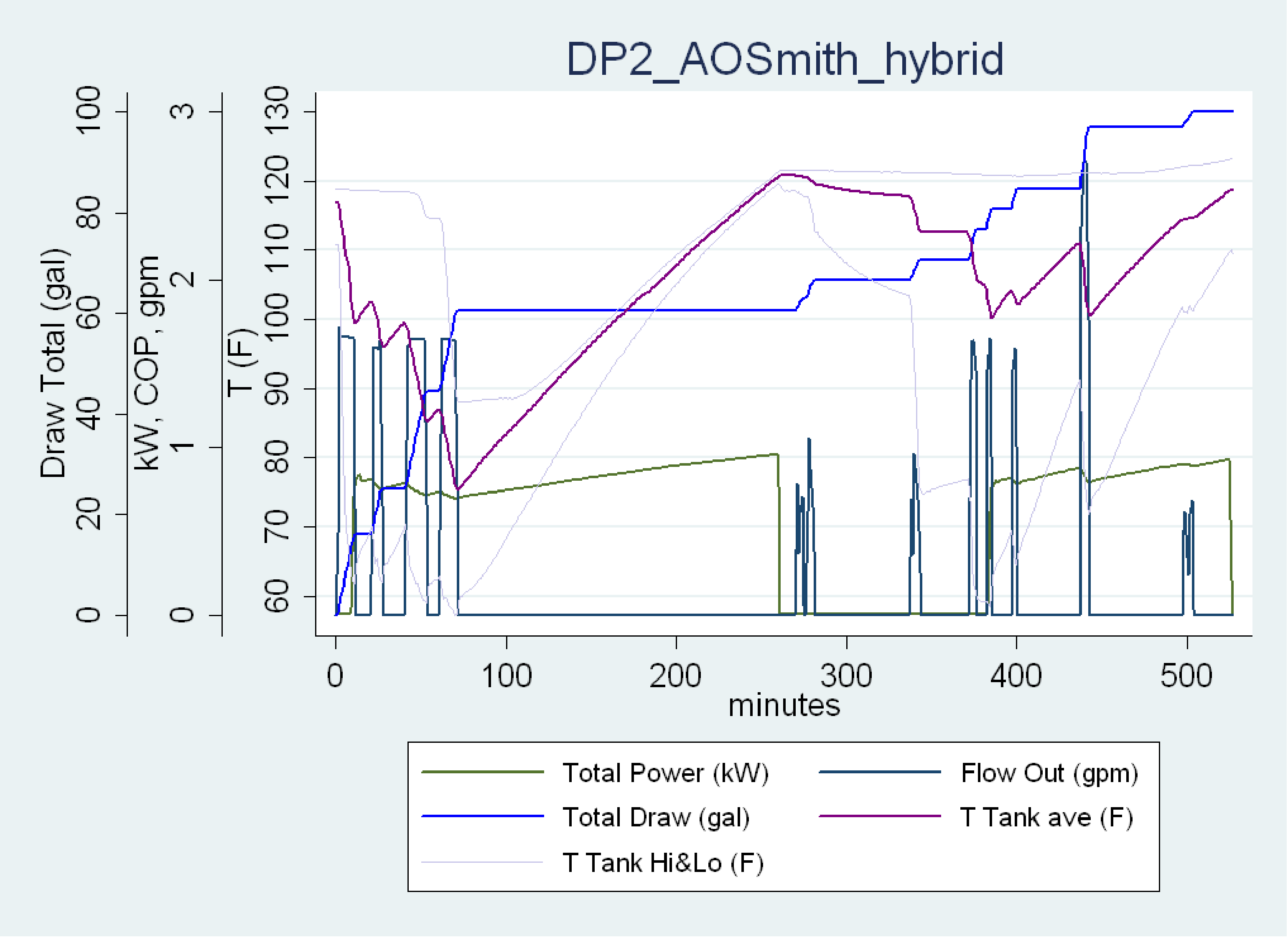
DP-2, Both Segments, Rheem



DP-2, Both Segments, GE



DP-2, Both Segments, AO Smith



Draw Profile Additional Findings

- Tank storage capacity has a significant effect on efficiency.
  - Heat pump heating capacity is generally lower than resistance elements.
    - → It takes longer to heat the same amount of water
  - Larger tanks have more thermal storage which allows equipment to supply hot water for large draws longer and then recover tank with compressor only
- Circulation pumps destratify the tank and can compromise hot water delivery
- # of showers provided before outlet water drops below 105F or resistance elements turn on:
  - Rheem: 1
  - GE: 2
  - AO Smith: 4

Summary Findings

- Lab measured basic characteristics of equipment and performed DOE rating tests achieving results comparable to published data.
- Collected data to:
  - completely map compressor performance over all operating ranges
  - determine under what draw conditions units switch to resistance element
- Draw profiles show link between storage capacity and overall efficiency
- Key equipment findings:
  - Circulation pumps can destratify the tank potentially leading to compromised user experience
  - Rheem has limited low temperature compressor range leading to more element use
  - Both Rheem and GE storage capacity of 45 gallons tends to result in more element use especially around peak draw periods
  - AO Smith larger storage capacity of 75 gallons reduces element use

Q&A for Lab Testing

Space Interactions & Energy Use

- Baseline Inputs
- Field Data
- Annual Space Temperature Profiles
- COP Mapping
- Garage, Basement and Conditioned Space Install Energy Use
- Heating/Cooling System Interactions
- Energy Savings Estimates

Baseline Inputs

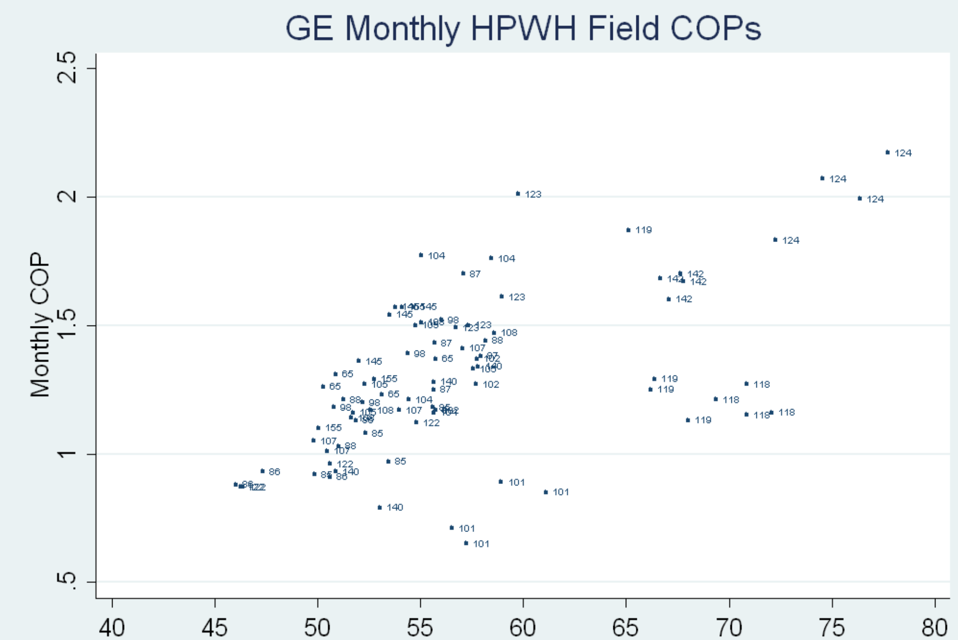
- Baseline water heating system:
  - Electric resistance, EF=0.904, 50 gallon capacity
    - RTF Efficient Tanks Measure:
      - http://www.nwcouncil.org/energy/rtf/measures/measure.asp?id=125
    - 6th Power Plan Worksheets:
      - http://www.nwcouncil.org/energy/powerplan/6/supplycurves/res/RESDHWFY09v1_1.XLS
- Energy use: 3655kWh/yr
  - Outlet-Inlet Water ΔT=77 F
  - 49 gal/day
  - Corresponds to 2.5 people at ~20gal/person
    - Historical note: 1169kWh*(2.6 people) + 624kWh = 3663kWh

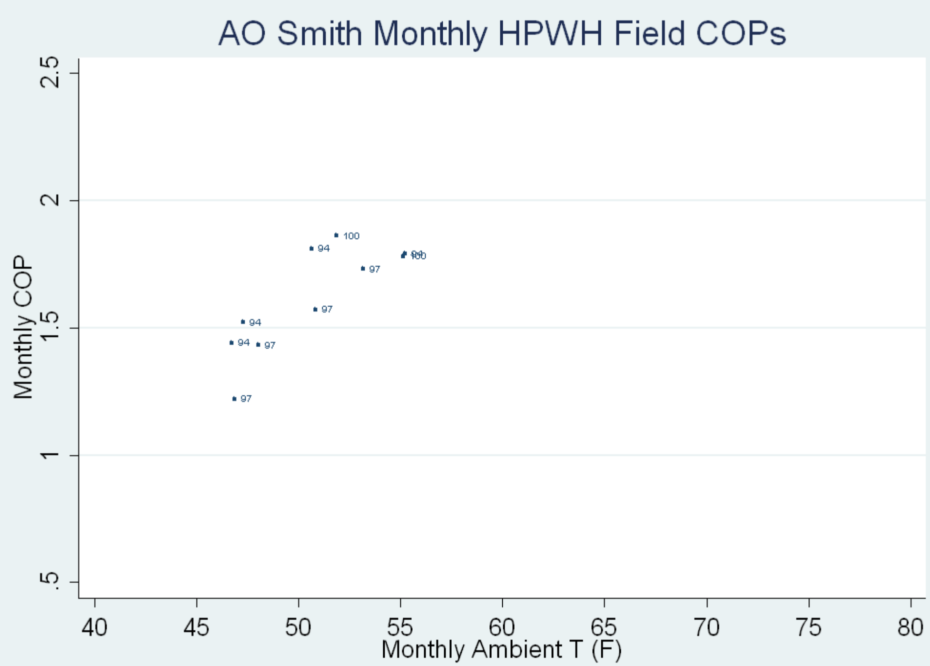
Field Data from BPA Study

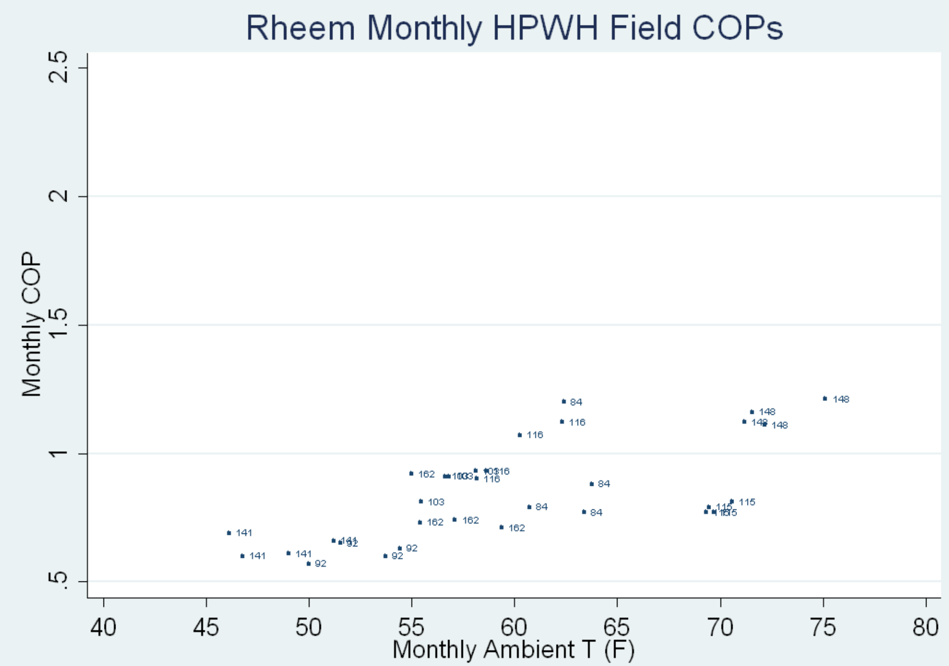
- Study conducted by EPRI is currently underway
  - Sites selected are not a random or an engineered sample
- Examined four months of available data which has the following characteristics:
  - Jan-Apr 2011
  - 32 sites. GE: 21, AO Smith: 3, Rheem: 8
  - Climate categories:
    - PDX: 16, SEA: 8, SPO: 3, BOI: 1, KAL: 4
  - Install locations:
    - Garage: 21, Unhtd Basement: 5, Unhtd Utility Rm: 1: Conditioned Space (any): 5
  - Average daily hot water use: 47.5 gallons
  - Average Outlet – Inlet Water ΔT=70.3 F

Monthly COP vs T_{amb}

- Averaged by daily volume
- Labels in graphs are site ids
- COPs lower than rated EF because T_{amb} lower and use of resistance elements

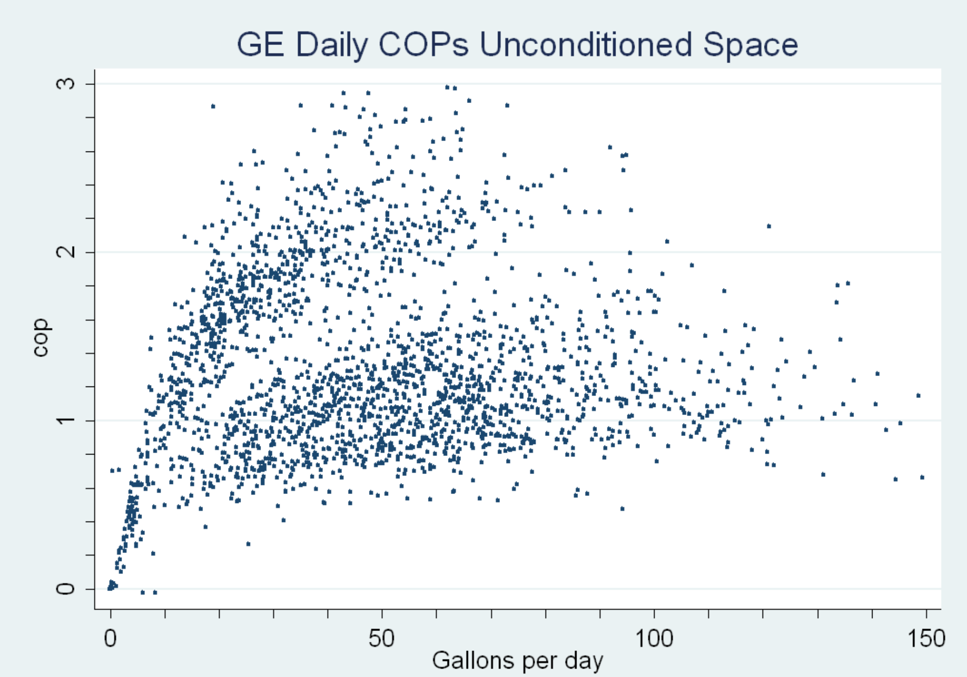


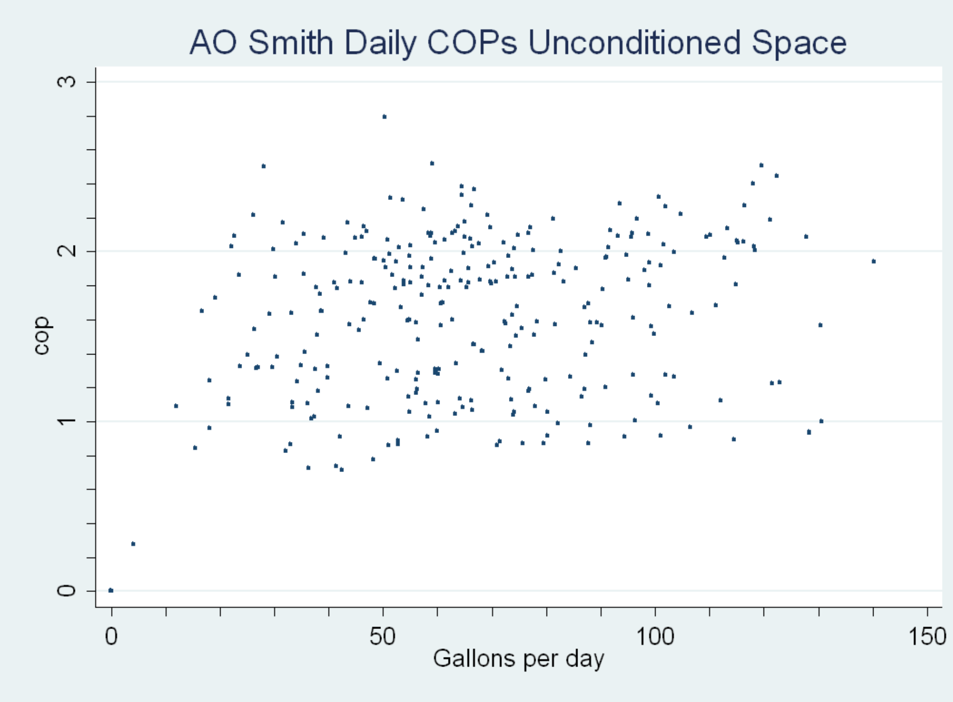


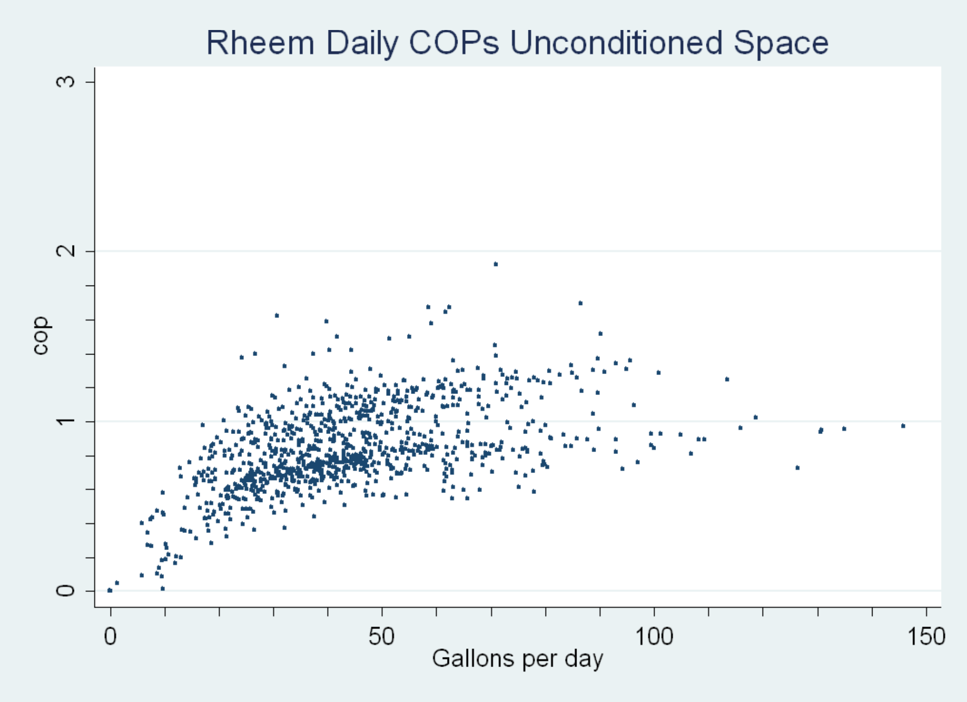


Daily COP vs GPD

- Graphs show expected low COP with low draws.



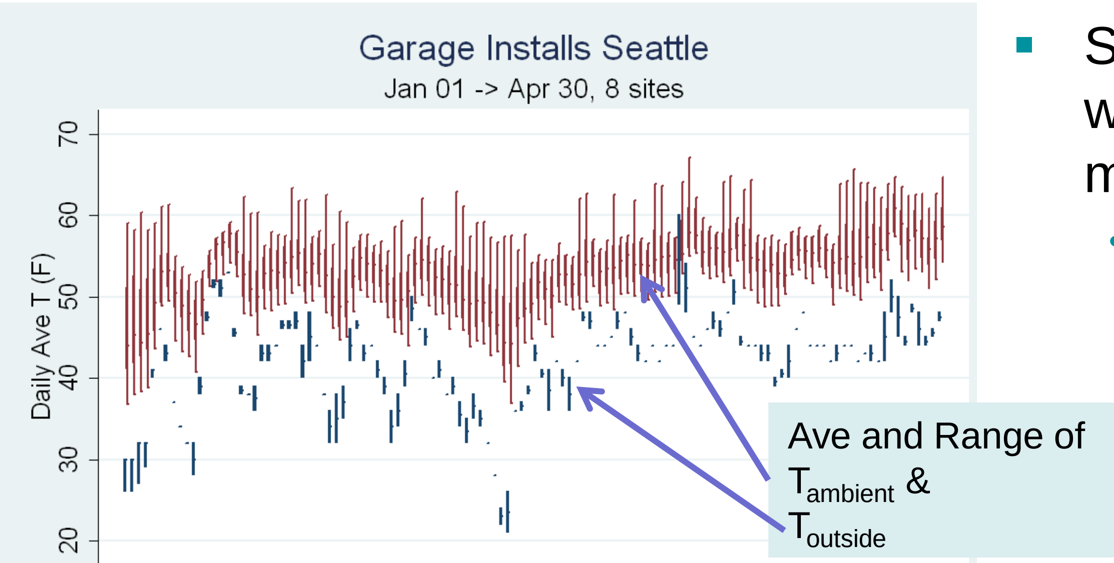


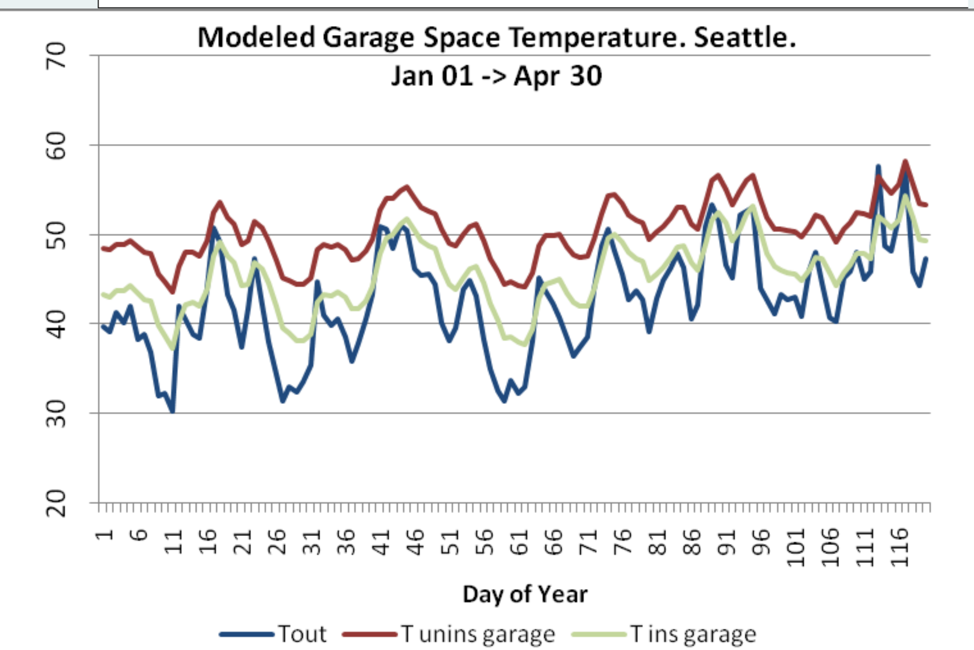


Energy Use Calculation Strategy

- Create annual temperature profiles (in bins) for spaces where the water heater is installed:
  - Garage, unheated basement, interior conditioned space
  - Use field data to inform T bin profiles
- Create COP map vs temperature from field and lab data
  - Field data used to determine how frequently resistance elements are used
  - Lab data gives the compressor COP and is used to extrapolate equipment operation to operating temperatures for which there is not yet field data
- COP map applied to the T bin profile to produce an annual COP estimate

Temperature Profile Matching



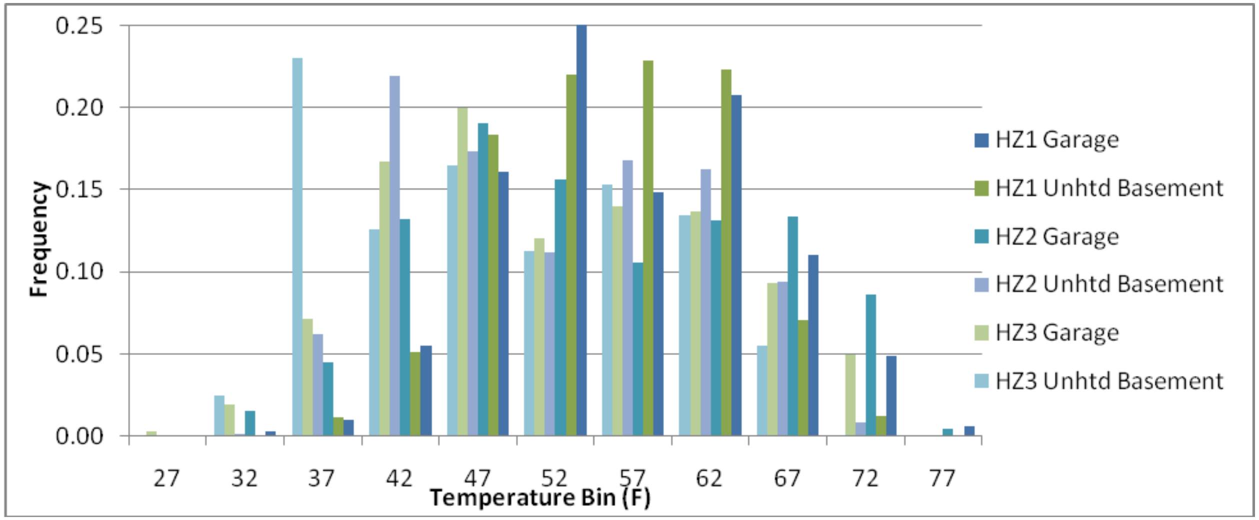


- Simulated garage installations with SUNCODE and compared to measured temperatures.
  - Considered 2 scenarios as sensitivity analysis:
    - Insulated and uninsulated between house and garage.
    - Neither scenario had internal gains in garage which may have increased measured temperature but we lack enough info to characterize gains well for modeling
  - Only garage installs for SEA & PDX had enough sites to use for comparison
    - SEA example at left
  - Warmer of the 2 scenarios better matched field data so used that models to develop T bin profiles

Temperature Bin Profiles

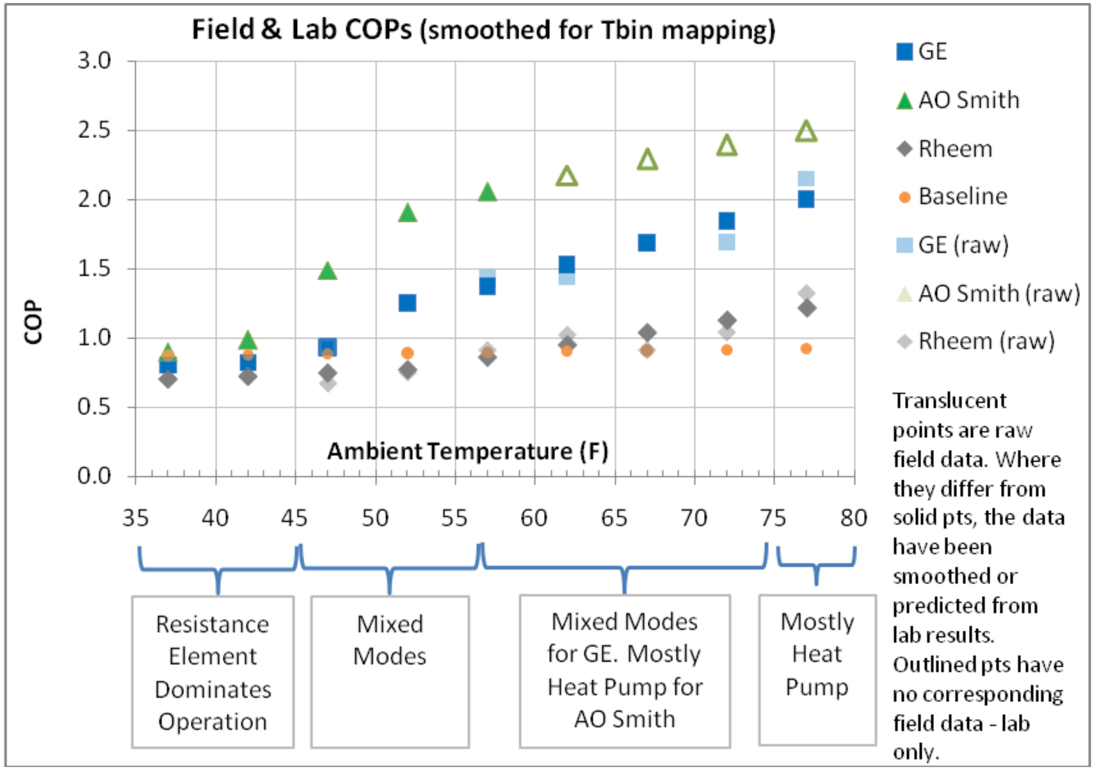
Tbin (center)	HZ1		HZ2		HZ3	
	Garage	Unhtd Basement	Garage	Unhtd Basement	Garage	Unhtd Basement
77	0.01	0.00	0.00	0.00	0.00	0.00
72	0.05	0.01	0.09	0.01	0.05	0.00
67	0.11	0.07	0.13	0.09	0.09	0.05
62	0.21	0.22	0.13	0.16	0.14	0.13
57	0.15	0.23	0.11	0.17	0.14	0.15
52	0.25	0.22	0.16	0.11	0.12	0.11
47	0.16	0.18	0.19	0.17	0.20	0.16
42	0.05	0.05	0.13	0.22	0.17	0.13
37	0.01	0.01	0.05	0.06	0.07	0.23
32	0.00	0.00	0.01	0.00	0.02	0.02
27	0.00	0.00	0.00	0.00	0.00	0.00

- Frequency values are percent of time in a year for a given temperature bin based on daily averages.



COP Map

- Using lab and field results, created a COP map vs ambient T
  - Field data smoothed to create stable, less noisy trend that matched lab results.
- Electric resistance element use has substantial influence on COP especially at the mid and low T_{amb}
- Baseline use also impacted by ambient temperature: lower temperature leads to increased standby losses.
- In all resistance heat mode, $COP_{HPWH} < COP_{baseline}$ because HPWH tank standby losses are greater



Annualized COPs & DHW Energy Use

		Annual COP			Annual Energy Use (kWh)		
		HZ1	HZ2	HZ3	HZ1	HZ2	HZ3
Garage	GE	1.3	1.3	1.1	2492	2610	3062
	AO Smith	1.9	1.8	1.4	1716	1827	2303
	Rheem	0.9	0.8	0.8	3839	3899	4235
	Baseline	0.9	0.9	0.9	3691	3700	3748
Unheated Basement	GE	1.3	1.2	1.1	2559	2794	2982
	AO Smith	1.9	1.7	1.5	1739	1968	2136
	Rheem	0.8	0.8	0.8	3916	4024	4167
	Baseline	0.9	0.9	0.9	3696	3711	3727
Conditioned Space	GE		1.7			1960	
	AO Smith		2.3			1443	
	Rheem		1.0			3188	
	Baseline		0.9			3637	

- Energy use for water heater only – does not include interactive effects on heating & cooling
- Conditioned space assumed to have constant 67F temperature

Heading / Cooling Interactions

- HPWHs extract heat from whatever space they occupy.
  - The more the resistance element is used, the less heat they extract
  - The warmer the ambient environment, and, hence, higher COP, the more heat is extracted
  - Tank standby losses add heat back to the space
- Heat extracted from conditioned space in heating season will require more heat input from the heating system
- Heat extracted from conditioned space in cooling season will require less cooling energy for those houses which already use cooling
- Heat extracted from buffer space will decrease buffer space T & increase heat loss from the house whereby increasing the heating load (although significantly less than an interior installation)

- Overall, this is a highly interactive system but one that we don't get to model fully interactively for this analysis.

HVAC System - Interaction Impacts

- Some energy to heat the water always comes from the resistance elements and the compressor. Other energy comes from outside air (buffered spaces) or the heating system.
- Different heating/cooling impacts based on the HVAC system type
- Gas furnace houses:
  - Water heating energy will come in the form of increased therm usage.
  - Creates a hybrid fuel water heater
- Electric resistance heat:
  - Energy comes in the form of increased kWh at COP 1 –
  - This looks a lot like heating the water with resistance elements
- Heat pump space heat:
  - Energy comes in the form of increased kWh usage but has far less of an impact than resistance heated homes.
- Cooling benefit to houses with existing cooling

Modeling the Interactions

- Heat extracted looks like a negative internal gain to a simulation program.
- Modeled with SUNCODE for garages and SEEM for unheated basement and interior installations
  - Used a constant hourly internal gains schedule to compare before and after results.
    - Tank water heaters do not run on a constant basis but rather have several on/off periods throughout the day. The constant hourly schedule misses this but does capture the total heat extracted per day.
  - For buffer spaces, used a seasonal schedule to simulate the increase in heat extracted with increased COP and decreased resistance element use that results from warmer temperatures
  - Buffer spaces modeled using a “generic” HPWH (mix of GE and AO Smith equipment) to determine heat extracted per day.
    - Rheem excluded from buffer space interaction analysis because it predominantly used resistance element in those temperature conditions.
  - Conditioned space scenarios model different levels of negative internal gains corresponding to each equipment’s COP at room temperature.

Buffer Space Installs Htg/Clg Impacts

Garage Installation Impacts by System Type:				
		HZ1	HZ2	HZ3
Zonal Resistance	kWh	-184	-177	-203
Gas Furnace AFUE 90	therms	-8	-7	-9
Heat Pump HSPF 8.5	kWh	-81	-85	-104
Cooling	kWh		10	
Basement Installation Impacts by System Type:				
		HZ1	HZ2	HZ3
Zonal Resistance	kWh	-421	-451	-523
Gas Furnace AFUE 90	therms	-16	-17	-20
Heat Pump HSPF 8.5	kWh	-168	-196	-240
Cooling	kWh		63	

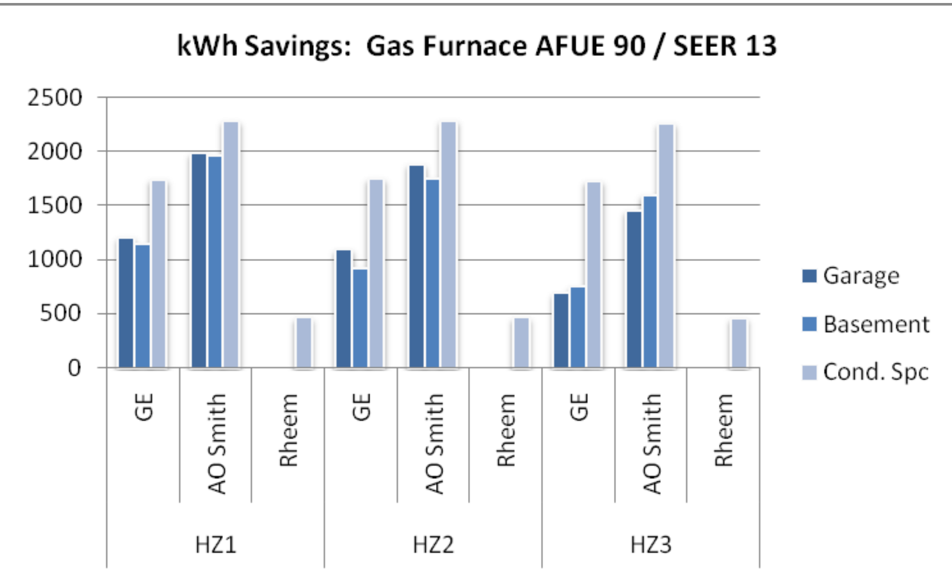
- Unheated basements more closely couple to house than garages so impacts are greater (garage air change rates to outside are higher)
- Cooling impacts are minimal and calculated for regional average cooling climate only

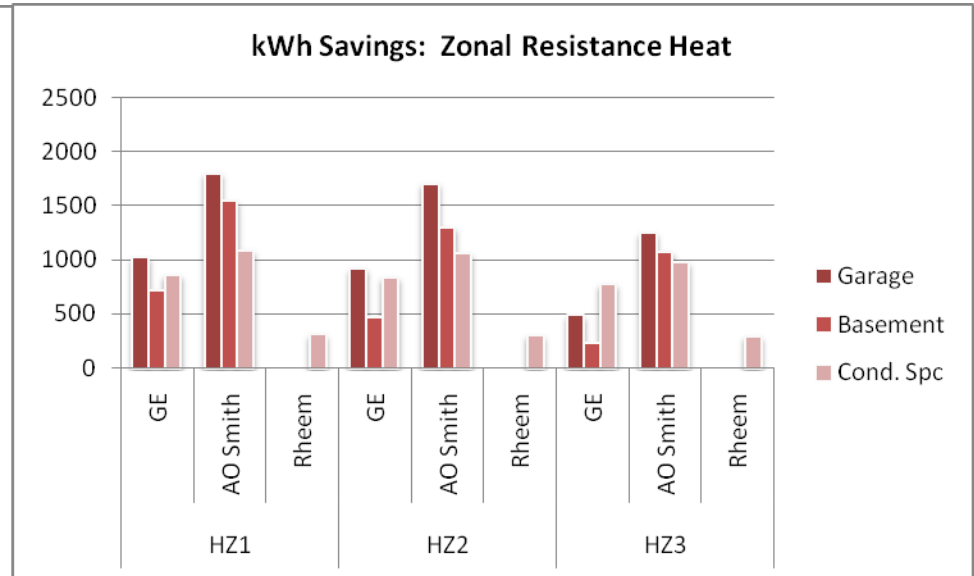
Conditioned Space Htg/Clg Impacts

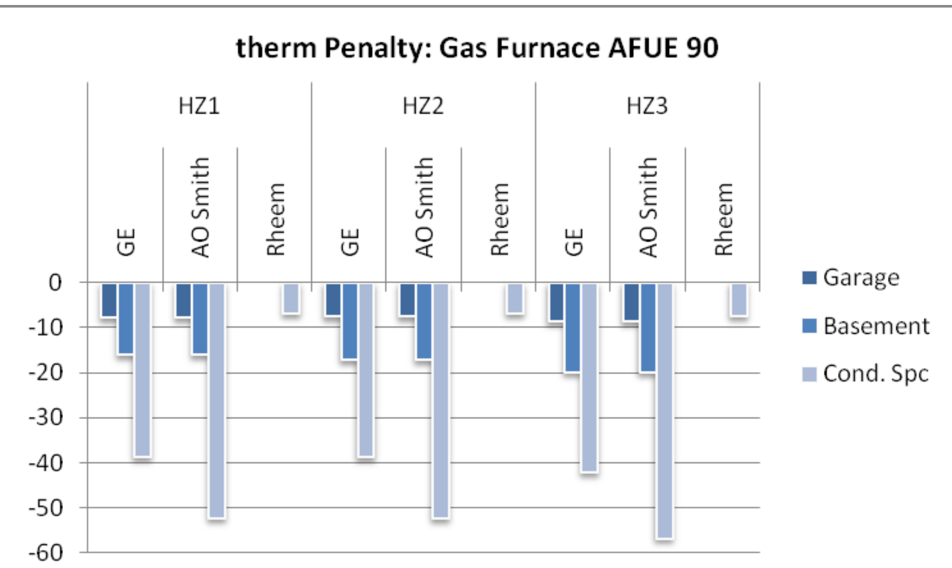
- Large variation in impacts due to operational strategy of equipment.
  - Those operating with more compressor at higher COP extract more heat from the ambient environment.
- Extra heating input depends primarily on HVAC equip and distribution system efficiency
  - Assumed PTCS equip and ducts so these savings comparable on “last measure in” basis. Less efficient equipment would increase magnitude of impact

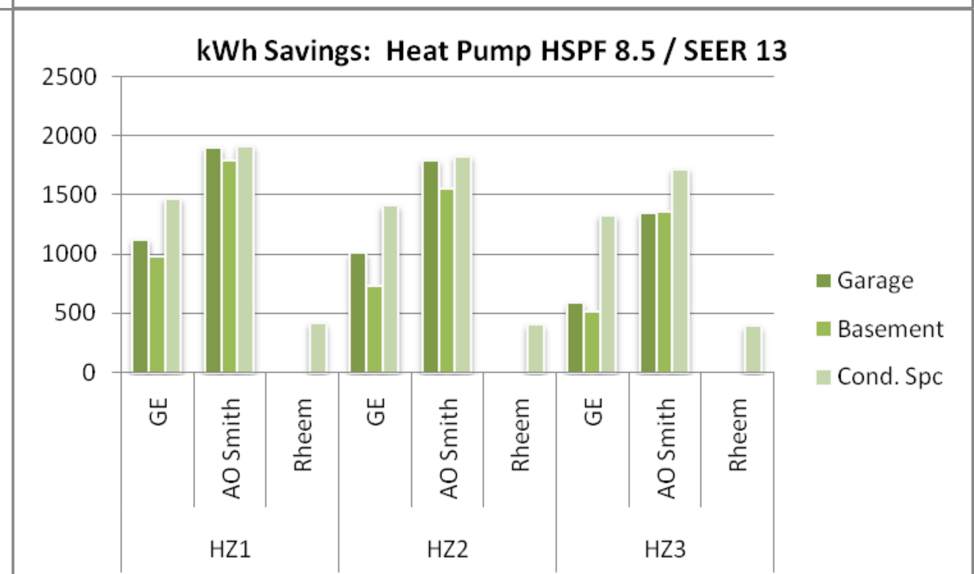
Conditioned Space Impacts				
HVAC Type	HPWH	HZ1	HZ2	HZ3
		therms/yr		
Gas Furnace AFUE 90	GE	-39	-39	-42
	AO Smith	-52	-52	-57
	Rheem	-7	-7	-7
		kWh/yr		
Heat Pump HSPF 8.5	GE	-269	-347	-459
	AO Smith	-365	-472	-622
	Rheem	-46	-60	-80
		kWh/yr		
Zonal Resistance	GE	-823	-845	-907
	AO Smith	-1114	-1139	-1223
	Rheem	-143	-148	-159
		kWh/yr		
Cooling SEER 13	GE	91		
	AO Smith	121		
	Rheem	17		

Energy Savings with Interactions









Energy Savings with Buffer Space Interactions

GARAGE				
		HZ1	HZ2	HZ3
Gas Furnace AFUE 90		kWh/yr		
	GE	1200	1090	686
	AO Smith	1975	1873	1445
		therm/yr		
	GE	-8	-7	-9
	AO Smith	-8	-7	-9
		kWh/yr		
Zonal Resistance	GE	1016	913	483
	AO Smith	1792	1696	1242
		kWh/yr		
Heat Pump HSPF 8.5	GE	1119	1004	583
	AO Smith	1894	1788	1342

UNHEATED BASEMENT				
		HZ1	HZ2	HZ3
Gas Furnace AFUE 90		kWh/yr		
	GE	1137	918	745
	AO Smith	1957	1744	1591
		therm/yr		
	GE	-16	-17	-20
	AO Smith	-16	-17	-20
		kWh/yr		
Zonal Resistance	GE	717	467	222
	AO Smith	1537	1293	1068
		kWh/yr		
Heat Pump HSPF 8.5	GE	970	722	505
	AO Smith	1790	1548	1351

- Savings in unheated basements generally less because heating penalty greater and no high summer season temperatures to benefit COP

Energy Savings with Cond. Space Interactions

CONDITIONED SPACE				
		HZ1	HZ2	HZ3
Gas Furnace AFUE 90 with SEER 13			kWh/yr	
	GE	1735	1741	1720
	AO Smith	2270	2278	2250
	Rheem	460	461	457
			therm/yr	
	GE	-39	-39	-42
	AO Smith	-52	-52	-57
	Rheem	-7	-7	-7
Zonal Resistance (no cooling)			kWh/yr	
	GE	853	832	770
	AO Smith	1080	1055	971
	Rheem	306	300	290
Heat Pump HSPF 8.5			kWh/yr	
	GE	1465	1403	1324
	AO Smith	1906	1822	1715
	Rheem	413	402	387

Next Steps

- Ecotope to provide written report at the end of August
  - BPA will review and subsequently post
- Propose measure and savings estimates to the RTF

Q & A

Contact Information

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